9-22-2000

Capacity fairness of WDM networks with grooming capabilities

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Recommended Citation

Thiagarajan, Sashisekaran and Somani, Arun K., "Capacity fairness of WDM networks with grooming capabilities" (2000). *Electrical and Computer Engineering Conference Papers, Posters and Presentations*. 170.
https://lib.dr.iastate.edu/ece_conf/170

Abstract

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Keywords

Wavelength-routing, Capacity Fairness, Traffic Grooming, Blocking Probability

Comments

This proceeding is published as Thiagarajan, Sashisekaran, and Arun K. Somani. "Capacity fairness of WDM networks with grooming capabilities." In *OptiComm 2000: Optical Networking and Communications*, vol. 4233, pp. 191-201. International Society for Optics and Photonics, 2000. DOI: 10.1117/12.401818

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Sashisekaran Thiagarajan, Arun K. Somani, "Capacity fairness of WDM networks with grooming capabilities," Proc. SPIE 4233, OptiComm 2000: Optical Networking and Communications, (22 September 2000); doi: 10.1117/12.401818

SPIE.

Event: Opticomm 2000, 2000, Richardson, TX, United States

Capacity Fairness of WDM Networks with Grooming Capabilities

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ABSTRACT

This paper addresses the issue of *capacity fairness* in WDM networks with traffic grooming capabilities, supporting lower-rate circuit-switched traffic streams. Traffic grooming in WDM networks, is defined as the act of multiplexing, demultiplexing and switching lower rate traffic streams onto higher capacity lightpaths. In such a network, in addition to add/drop and full wavelength switching features, some or all of the network nodes can be provided with the capability to switch lower-rate traffic streams from one wavelength on an input port to another wavelength on an output port. Call requests arrive randomly and can request a lower-rate traffic connection to be established between the node pair. The call requests that ask for capacity nearer to the full wavelength capacity are bound to experience higher blocking than those that ask for a smaller fraction. This difference in loss performance is more pronounced as the traffic switching capability of the network is increased. In this paper, we study the capacity fairness of existing dynamic wavelength assignment algorithms. Connection admission control mechanisms can be used along with wavelength assignment schemes to improve the fairness among connections with different capacities at the cost of increase in the overall blocking performance. In this paper, we propose a simple, admission control algorithm to attain fairness in capacity. The algorithm provides good capacity fairness while at the same time does not over-penalize the overall blocking performance.

Keywords: Wavelength-routing, Capacity Fairness, Traffic Grooming, Blocking Probability

1. INTRODUCTION

Wavelength Division Multiplexing(WDM) divides the large bandwidth available in optic fiber into multiple channels with each of the channels operating at different wavelengths and at data rates of around 2.5 Gbps (OC-48) to 10 Gbps (OC-192). With current advances in WDM and in high-speed electronic routing/ switching, it is likely to be the case that next-generation broadband networks will employ a hybrid, layered architecture, using both optical WDM and electronic switching technologies. In such networks, a significant gap exists between the huge transmission capacity of WDM fibers and the electronic switching capacity. Consequently, these networks are limited more by the electronic switches and routers at the nodes than by the link transmission bandwidth.

Wavelength-routing technology, using Optical Add/Drop Multiplexers (OADMs) and Optical Crossconnects (OXCs), helps limit the amount of electronic TDM equipment, offers the advantages of wavelength reuse, scalability and helps overcome the electronic bottleneck. OADMs allow wavelengths to be selectively dropped at the nodes or optically pass through the node unaffected. In addition, OXCs enable space-switching of wavelengths from one port to another and help in establishing circuit-switched connections called lightpaths between the nodes. This enables optical passthrough at the WDM layer and eliminates the need to electronically process all the traffic at the nodes.

In such WDM networks, while the wavelength has transmission capacity at gigabit per second rates (eg. OC-48 or OC-192 and on to OC-768 in the future), the network may be required to support traffic connections at rates that are lower than the full wavelength capacity. These low-rate traffic connections can vary in range from say, STS-1 (51.84 Mbps) capacity upto the full wavelength capacity. In addition, for networks of practical size, the number of available wavelengths is still lower by a few orders of magnitude than the number of source to destination connections that need to be made. Thus the solution lies in efficiently *grooming* the traffic onto the wavelengths. *Traffic grooming*

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in WDM networks can be defined as the act of multiplexing, demultiplexing and switching lower rate traffic streams onto high capacity lightpaths. Efficient traffic grooming improves the amount of optical passthrough and wavelength utilization in the network. Traffic grooming can be performed at two points in the network. The act of multiplexing and demultiplexing the (electrical) traffic streams onto the (optical) wavelengths can be performed by the OADMs present at the nodes. The act of switching the traffic streams from one wavelength to another can be performed at the crossconnects at the nodes. Switching at these nodes can be performed in space, time and wavelength so that a traffic stream occupying time slots on a wavelength on a fiber can be switched to a different time slot on a different wavelength on another fiber. However, this *traffic stream switching* capability comes at the cost of increased crossconnect complexity. In addition to the space-switching of wavelengths, the crossconnect may have to be provided with wavelength conversion and time-slot interchange equipment. Currently, all-optical wavelength conversion and all-optical time-slot interchange devices are still not commercially available and it is more attractive to use electronic methods of implementation to incorporate these features into the network. In the future, it may be possible to perform all-optical traffic grooming. Such all-optical traffic grooming networks may prove to be more cost-effective and manageable than their electronic counterparts.

1.1. Background

Most of the work in traffic grooming[1,2] has been in the area of providing efficient network designs in WDM rings and have proposed solutions to improve the overall network cost. Traffic grooming algorithms for assigning low rate circuits to wavelengths in WDM rings have also been proposed.[3,4,5,6] Specifically, these algorithms dealt with the minimization of the cost of higher-layer electronics whose cost dominates over the cost of wavelengths and optical equipment. The blocking performance of traffic grooming WDM networks with arbitrary topologies was studied in.[7] It was shown that the blocking performance is not only affected by the link traffic and the routing and wavelength assignment strategy, it is also affected by the arrival rates of different low-rate traffic streams, their respective holding times and more importantly, the capacity distribution of the wavelengths on the links. A link-independence model was also presented which took into account the capacity distribution of wavelengths to calculate the blocking performance. In such networks, call requests arrive randomly and can ask for a low-rate traffic connection to be established between the source and destination. Under dynamic traffic conditions, call requests that ask for capacity nearer to that of the full wavelength experience higher probability of blocking than those that ask for a smaller fraction. In fact, the difference in blocking performance between the high and low capacity traffic streams becomes more significant as the traffic stream switching capability of the network increases. This difference in blocking performance for different capacities is directly affected by the routing and wavelength assignment policy that is used to route the call request. Hence, it is important that a call request is provided service in a *fair* manner commensurate with the capacity it requests. This *capacity fairness* is different from the fairness measure based on hop count that has traditionally been addressed in the literature.[8,9]

Birman and Kershenbaum[9] proposed two techniques for fairness improvement with respect to hop length. In the first method called Reservation technique, they reserve wavelengths exclusively for longer-hop paths on every link. However, the longer-hop paths can also compete with the shorter-hop paths for other wavelengths. In their second method called Protecting Threshold technique, the traffic on long paths is protected from the traffic on short paths by admitting the short path traffic only when the link utilization is below a given threshold. This leads to fairness in blocking. Harai et al.[8] proposed a limited alternate routing method to improve fairness. In this method, long paths have a larger number of alternate paths than short paths. By limiting the number of alternate connections in short paths, we can accommodate more long path connections. These methods introduce fairness by regulating the admission of connection requests based on the path length at the expense of increase in overall blocking probability. They can be grouped into the general category of algorithms called *connection admission control* algorithms.

In optical networks without wavelength conversion, a lightpath should use the same wavelength throughout the route on all links of the path. This requirement is called the wavelength continuity constraint and contributes to the increase in probability of a call request being blocked. As the path length from source to destination increases, the blocking probability of the corresponding call request increases. Hence in a network with no wavelength conversion, long paths have higher blocking probability than short paths. Wavelength conversion can be employed at the network nodes to reduce the blocking of longer-hop connections. Wavelength conversion for WDM networks was studied in[10–].[13] It was shown that wavelength converters reduce wavelength conflicts and improve the performance by reducing the blocking probability. On the other hand, an increase in the network's wavelength conversion capability results in the network admitting longer-hop paths, which consumes more network resources. This increases the blocking probability of shorter-hop paths, compared to their performance in networks with no wavelength conversion.

In general,when we have to service call requests that dynamically arrive and depart from the network in a random manner, we rely on a dynamic routing and wavelength assignment algorithm (D-RWA). This D-RWA algorithm is responsible for selecting a suitable route and wavelength among the various choices available for establishing the call and hence plays a key role in determining the performance of such networks. Usually, the common metric in evaluating the performance of D-RWA algorithms is the blocking probability. However, a good D-RWA algorithm for traffic grooming networks should treat all call requests in a "fair" manner while ensuring efficient utilization of the network. Usually, the problem of D-RWA is separated into the subproblems of routing and wavelength assignment and solved independently. Current Dynamic Wavelength Assignment (D-WA) algorithms, such as first-fit (FF),[14] random assignment (R),[16] most-used (MU)[17] and Max-Sum (MS),[18] were designed in a network scenario where the full wavelength was the basic unit of bandwidth. However, in WDM networks capable of traffic grooming, the basic unit of bandwidth is a traffic stream whose capacity can be less than that of a wavelength. The blocking and fairness performance of these algorithms in such a traffic grooming scenario is not known. In this paper, we study the fairness performance of traditional D-WA algorithms in terms of capacity, in a traffic grooming WDM network. We find that these algorithms do not treat call requests of different capacities in a fair manner. This motivates the need for a good mechanism to provide capacity fairness. We propose a new connection admission control scheme which can be used along with existing wavelength assignment algorithms to attain fairness in capacity. Our proposed algorithm achieves fairness in capacity while not over-penalizing the network blocking performance.

The rest of the paper is organized as follows. In Section II, we establish the network model used in the paper. In Section III, we provide a definition of capacity fairness and specify the fairness conditions that an efficient algorithm needs to satisfy. In Section IV, we describe the connection admission control algorithm which is used to attain capacity fairness. In Section V, the fairness performance of existing D-RWA algorithms and the proposed admission control scheme are studied using simulation results. Finally, the conclusions are provided in Section VI.

2. NETWORK MODEL

As described in,[7] we consider a WDM network with network nodes of two types: *Wavelength-Selective Crossconnect (WSXC)* nodes and *Wavelength-Grooming Crossconnect (WGXC)* nodes. These networks nodes are interconnected by bi-directional or uni-directional fiber-optic links. WSXC nodes have OXCs, which space-switch full wavelengths from an input port to an output port, and OADMs, which groom the traffic streams onto the added/dropped wavelengths. However, WSXC nodes do possess constrained form of grooming but cannot switch traffic streams between wavelengths. WGXC nodes, in addition to having the full functionality of a WSXC, are capable of time-slot interchange and can switch lower-rate traffic streams from a set of time slots on one wavelength on an input port to a different set of time slots on another wavelength on an output port. We assume that this switching is fully non-blocking and can be performed for all wavelengths from any input port to any output port. Hence, full wavelength conversion capability is implicitly available at the WGXC node. Such a node is said to have *full grooming* capability. If switching of lower-rate traffic streams is performed only on a restricted number of wavelengths, then the node is said to have *limited grooming capability.* We assume that all the WGXC nodes in our network are provided with full grooming capability. Since the hardware complexity of WGXC nodes is more than that of WSXC nodes, WGXC nodes also cost significantly more than WSXC nodes. Therefore, we assume the practical situation in which only some of the nodes of the network are WGXC nodes and the rest of the nodes are WSXC nodes. Such a network is referred to as a *sparse grooming network.* On the other hand, a network with only WSXC nodes and no WGXC nodes is referred to as a *constrained grooming network*, since grooming is constrained to the OADMs at the nodes.

We assume a dynamic traffic model in which low-rate traffic sessions arrive and depart from the network in a random manner. Such a traffic session is routed along a path traversing through intermediate WSXC and WGXC nodes between the source and destination. If the path traverses through one or more intermediate WGXC nodes then the traffic session involves more than one lightpath. Lightpaths between the source, destination or intermediate WGXC nodes satisfy the wavelength continuity constraint, that is, the traffic stream occupies the same wavelength on all the links of the path between the source, destination or intermediate WGXC nodes. However lighpaths between WGXC nodes can be routed on different wavelengths. In this manner, each lightpath typically carries many multiplexed lower-speed traffic streams. During connection setup, it should be confirmed whether the lightpaths, that have been established earlier, have the required amount of capacity before they can be used to accommodate the new traffic session.

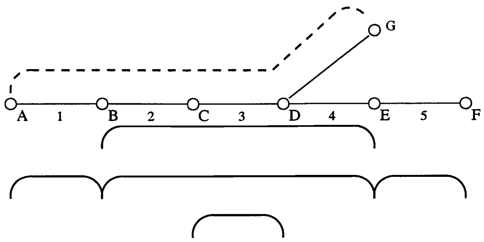

Figure 1. Network Example

2.1. Connection Setup and Release

The connection setup and release procedure in traffic grooming networks is different from the lightpath establishment process of conventional wavelength routing networks. Consider an example of a sub-network, shown in Figure. 1, which can be a part of a bigger mesh network. Assume a single wavelength is currently available on the path from A to F. Let the capacity of the wavelength be C. Further assume that all the nodes on the path are WSXC nodes. Suppose a request arrives for a connection from node B to E for a line capacity of $C/4$. This is established immediately on the available wavelength by configuring the OADMs at nodes B and E, and by configuring the OXCs at nodes C and D. Note that we add/drop the wavelength only at nodes B and E, and not at nodes C and D. Let a second request arrive for a connection from node A to node F for a line capacity of $C/4$. This is also established on the same wavelength by setting up lightpaths from A to B and from E to F, and by using the same lightpath on the wavelength between B to E that was established for the first connection. In this process, the first traffic stream is not disturbed. The wavelength is now add/dropped at four nodes, namely, A, B, E and F. Let a third request arrive for a connection from A to G for line capacity $C/4$. However, this connection cannot be established on the wavelength and will be blocked. The reason is, the path for the third connection request from A to G deviates away from the path of the lightpath on the wavelength and node D is only a WSXC node.

Let a fourth request arrive for a connection from node C to D for a line capacity of $C/4$. At this point, we have two options. (a) We can assume any lightpath that has been established should not be disturbed. Therefore, the traffic stream cannot be established on the same wavelength and is blocked. (b) However, if a temporary disturbance to the lightpath is acceptable. We can establish the third call on the same wavelength by add/dropping the wavelength at node C and D. The lightpath is now split into three parts. This temporary disturbance can be made possible by the presence of fast OADMs and fast reconfigurable OXCs at the nodes. For our network model, we assume the latter case (option *b*) and assume the nodes have fast OADMs and OXCs. On the other hand, if nodes C and D happen to be WGXC nodes, then it is possible to satisfy all the call requests.

When a call leaves the network, the lightpaths that are used to hold the traffic connection release the capacity used by the traffic stream. However, the lightpaths themselves might continue to operate over the wavelengths since they might have other traffic streams multiplexed over them. If the traffic stream was the sole one to have used the lighpath, then the lightpath itself can be released and the wavelengths on the links can be freed.

2.2. Assumptions

The following assumptions are used in our network simulation model:

1. The network consists of N nodes with L links. Each link is bidirectional and consists of a pair of fibers with W wavelengths each in each direction.
2. Each wavelength, with capacity C, has a line-speed indicated by a parameter g (C is assumed to be divisible by g) referred to as the *granularity*. A lightpath that traverses a wavelength can support a maximum of g traffic streams. In other words, atmost g low-rate traffic streams can be multiplexed onto the lightpath. The line-speed of a traffic stream can vary from 1 (of capacity C/g) to g (full wavelength capacity C). We define a traffic stream of line-speed j as a *Class j* traffic stream. A call that requests a *Class j* traffic stream is referred to as a *Class j* call request.

3. Call requests arrive at a node according to a Poisson process with rate λ. Each call is equally likely to be destined to any of the remaining $N-1$ nodes. The arrival rate of calls λ_{sd} at a node pair $< s, d >$ is $\lambda/(N-1)$. Each call can request a line speed j, where $1 \leq j \leq g$. The arrival rate of calls at a source-destination pair and requesting a line speed j is $\lambda_{sd}(j)$. In order to ensure capacity fairness in the arrival rate from source to destination, each set of Class j call requests should ask for the same combined capacity of calls in its class. In other words, if the combined capacity of calls to a node pair is say, Mg, then each class will contribute a capacity of M through its class arrivals. For example, class-1 traffic will have M call requests, class-2 will have $M/2$ call requests and similarly class-j traffic will have M/j call requests. Therefore, the probability, r_j that a call is of class-j is

$$r_j = \frac{1/j}{\sum_{i=1}^{g} 1/i}. \tag{1}$$

The expected value of j, $E\{j\}$ is then given by

$$\sum_{j=1}^{g} j r_j = \frac{g}{\sum_{i=1}^{g} 1/i}. \tag{2}$$

The *arrival rate per unit line-speed per s-d pair* is now defined as

$$\hat{\lambda_{sd}} = \lambda_{sd} E\{j\}. \tag{3}$$

Here the term "unit line-speed" refers to the capacity of the lowest granularity traffic stream that can be groomed onto the lightpath. $\hat{\lambda_{sd}}$ is essentially the arrival rate of calls at s-d pairs in the network if all call requests are of the lowest granularity, i.e. of class-1.

4. We assume fixed path routing i.e., each call uses a prespecified path. If the path cannot accommodate the call, then the call is assumed to be blocked and is lost.

5. Traffic requests cannot be split up among wavelengths on a link. Specifically, we assume that a traffic request can occupy only one wavelength on a link in the path.

6. The duration of each call request is assumed to be exponentially distributed with unit mean.

7. We also assume that there are enough WADMs i.e. receivers/transmitters at the nodes to handle all the traffic that originates from the nodes. The traffic from a node is then limited by the degree of the node, the number of wavelengths on the fibers and the capacity of the wavelengths.

3. CAPACITY FAIRNESS

In a network, where every user pays for the bandwidth he requests and consumes, it is important that every user get the same type of services as any other. The network system that offers the service must be fair and should not have any inherent bias against a particular subset of users. Although this concept of fairness is simple to understand, the exact definition of fairness however, is extremely case-dependent upon the networking issues involved. In addition, it is usually the case that any efforts by a control mechanism to ensure fairness on an issue results in the degradation of performance in other qualities of the network.

We define *capacity fairness* based on the following. In our network, call requests arrive randomly at a node pair. As explained previously, we have assumed the traffic model such that each class of traffic streams generates the same combined capacity worth of calls. However, calls of high capacity are blocked more often than those of small capacity. In fact, as the number of WGXC nodes i.e. the traffic stream switching capability in the network increases, there is more than an order of magnitude difference in blocking probability between calls of highest capacity and lowest capacity. A user who has knowledge of this unfairness can request his total required capacity in smaller traffic streams rather than as a whole. This is unfair to those users who are either ignorant of the unfairness and/or cannot request their total capacity in splittable flows. To prevent this i.e. to achieve capacity fairness, the blocking probability of a high capacity, say of line-speed m, call should equal the combined blocking performance of m calls of line-speed 1. Hence, we formally state the definition below:

Capacity fairness is achieved, when the blocking performance of m calls of line-speed n is equal to the blocking performance of n calls of line-speed m

At this point, we will assume that a user who requests capacity in terms of smaller number of calls will relinquish all his accepted calls immediately, even if one of them is blocked.* Therefore, if p_m is the blocking probability of a class-m call and p_n is the blocking probability of a class-n call, then to achieve capacity fairness:

$$1 - (1 - p_m)^n = 1 - (1 - p_n)^m \ \forall 1 \leq m, n \leq g. \tag{4}$$

In addition, an algorithm should achieve capacity fairness while keeping the overall blocking probability to an acceptable level. The overall blocking performance of the network can be defined in terms of the blocking probability per unit line-speed of the call requests. When capacity fairness is achieved, according to Eqn. 4, the blocking probability, p_j, of a class j call is the same as the blocking performance value, of j class-1 calls whose blocking probability is p_1 i.e.

$$p_j = 1 - (1 - p_1)^j \tag{5}$$

or

$$p_1 = 1 - \sqrt[j]{1 - p_j}. \tag{6}$$

Hence, using Eqn. 6 we can obtain an estimate of p_1 from p_j, We will refer to this estimate, $\hat{p_j}$, as the blocking probability per unit line-speed of a class j call. Now the overall network blocking probability per unit line-speed, $\hat{P}$, is given by

$$\hat{P} = \frac{\sum_{j=1}^{g} \hat{p_j}}{j}. \tag{7}$$

Recall from Section II, Equation 3 that $\hat{\lambda_{sd}}$ should be the equivalent arrival rate of calls at s-d pairs in the network if all call requests are of the lowest granularity, i.e. of class-1. For a given physical topology, if we assume that all incoming call requests are of class-1 and their arrival rate per node pair is $\hat{\lambda_{sd}}$, then the corresponding network blocking performance Q obtained is the best estimate for $\hat{P}$ when capacity fairness is achieved.

It is usually the case that the unfairness in an algorithm affects calls of the highest or the lowest capacity more than the calls of intermediate capacity. Keeping this in mind, we can give a good estimate of fairness using just the blocking performance of the highest and lowest capacity calls. Hence we can define the *fairness ratio* F_r for an algorithm running a network as the ratio of blocking probability per unit line-speed of the call with the highest line-speed (g), $\hat{p_g}$ to the blocking probability per unit line-speed of the call with the lowest line-speed (1), $\hat{p_1}$, or

$$F_r = \frac{\hat{p_g}}{\hat{p_1}}. \tag{8}$$

If the value of F_r is greater than 1, then the algorithm is said to favor high capacity call requests over low capacity call requests and vice versa. Therefore, if F_r for an algorithm is close to 1, then we can reasonably assume that the algorithm is also fair to calls of *all* capacities. Therefore a good admission control algorithm should ensure that $\hat{P}$ is close to Q and at the same time ensure capacity fairness using Equation 4 and have a fairness ratio close to 1.

*In this paper, we do not consider the scenarios, where the user can request a set of calls and accept or reject a subset of the accepted set.

4. CONNECTION ADMISSION CONTROL FOR CAPACITY FAIRNESS

In this section, we specify an algorithm that works along with any routing and wavelength assignment algorithm and introduces capacity fairness by exercising connection admission control using run-time blocking performance information. *Connection admission control* (CAC) is simply defined as the set of actions that are to be taken upon a call arrival in order to establish whether to accept or reject the connection request. Connection admission control relies on two factors.The first is that incoming call requests can specify their network requirements and the second is on the system's ability to measure, monitor and update the global state of the network, which in this case is the blocking performance of calls of various capacities at the nodes. Since the algorithm makes its decision to accept or reject a call based only on the current blocking values, the CAC algorithm is effective only after the network has been up and running for quite some time. This is because initially the blocking performance of the network may be inaccurate or may not be known. Due to the dependence of the algorithm on such a "warm-up" period, the algorithm should not be relied upon to provide capacity fairness during this period before attaining accurate and stable the run-time blocking probability attain accurate and stable values. Hence we assume that the CAC procedure is carried out when the network is in a state where there are previously established traffic streams and wavelengths are already assigned to those traffic streams in the network. Therefore the CAC algorithm uses the run-time blocking probabilities p_j of calls of class j in the network. The CAC algorithm is independent of the routing and wavlength assignment scheme and can work along with any routing and wavelength assignment scheme. The procedure for the CAC algorithm is as follows.

Assume a new call arrives for a node pair (s, d) and requests a capacity of j to be established from s to d:

1. Check if a traffic stream of capacity j can be established on the path i.e., enough capacity on wavelengths exist to carry the traffic stream. If the path cannot be established, reject the call.
2. Obtain an estimate of overall network blocking probability per unit line-speed, $\hat{P}$ from Eqn. 7 and the blocking probability per unit line-speed of the class j calls, $\hat{p_j}$, from Eqn. 6.
3. if $(\hat{p_j} \geq \hat{P})$ then accept the call and go to step 6.
4. let $q_m = (\hat{P} - \hat{p_j})/\hat{P}$.
5. Reject the call with probability q_m.
6. If the call is not rejected, start the wavelength assignment algorithm for the set of available wavlengths on the path to establish the connection. Update the blocking performance parameters.

We will refer to q_m as the *mean ratio*. Essentially, q_m is the rejection probability for the call. We can also obtain another estimation for rejection probability using the standard deviation D of blocking probability per unit line-speed values, $\hat{p_j}, 1 \leq j \leq g$. In this case q_D is given by

$$q_D = (\hat{P} - \hat{p_j})/(D) \tag{9}$$

We refer to q_D as the *deviation ratio.* q_D can be substituted for q_m in the algorithm. The fairness performance for the two cases of the algorithm will be shown in the next section. As the network services the calls that arrive, due to changes in network topology or traffic, it might happen that the current blocking of the network might differ significantly from the average blocking performance calculated over the lifetime of the network for the algorithm. To ensure accuracy in the estimation of blocking, we can use a rolling window of the most recent set of call arrivals and estimate the blocking performance using only those call arrivals rather than considering the complete set of calls since the network started operation.

5. NUMERICAL RESULTS ON 6X6 MESH-TORUS

We performed a simulation study of the call blocking performance in a 6×6 bi-directional mesh-torus network to study the capacity fairness property of various wavelength assignment algorithms and to evaluate the performance of our admission control scheme. Apart from the wavelength assignment schemes of Random (R) wavelength assignment, First-Fit(FF), Most-Used (MU) and MaxSum (MS), we have also considered a wavelength assignment scheme called Best-Fit (BF) that is unique to grooming networks. In Best-Fit wavelength assignment, among the available wavelengths for the traffic request, the traffic stream is assigned to that wavelength which has the least free capacity remaining when the incoming traffic stream is accommodated. We selected the mesh-torus network over other topologies like ring, hypercube, etc. because compared to the ring the mesh-torus has more connectivity which can help generate a good amount of traffic switching at the nodes. Also, compared to the hypercube, the average hop length is larger, which also gives rise to a good amount of load correlation between the links. For all the cases, we assumed the number of wavelengths (W) per fiber to be 5. We assumed the granularity (g) of the wavelength to be 4. This means that a traffic stream can ask for a minimum of one-fourth the capacity of the wavelength. We will illustrate some interesting results of the simulation study. In Fig. 2, we have plotted the fairness ratio versus the node load in Erlangs . We observe that for low node loads, the fairness ratio is high indicating that high capacity calls are favoured more than low capacity calls. But as the node load is increased, the network traffic as a whole is increased. This increases the blocking probability of both low capacity and high capacity connections. Hence all calls irrespective of whether they are high or low capacity start to experience blocking. We find that the Best-Fit does the best with respect to fairness and provides the fairness ratio that is closest to 1. On the other hand, the MaxSum algorithm, which provides the least overall network blocking than other wavelength assignment algorithms we have considered, has the highest fairness ratio at low loads in the network.

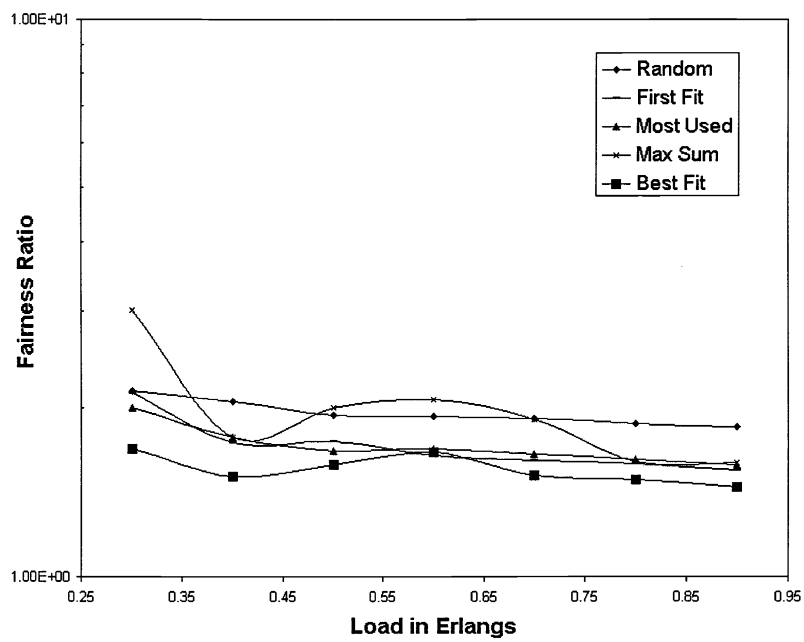

Figure 2. The fairness ratio versus node load in Erlangs for a bidirectional 6×6 mesh-torus with $g = 4$ and $W = 5$.

Next, we observe how the fairness ratio increases as the number of grooming nodes i.e., WGXC nodes, in the network is increased, in Fig. 3. We find that initially when no WGXC nodes are present in the network, the connections of high capacity have less blocking probability per unit line-speed than those with low capacity. But as the grooming capability of the network is increased,we find a reversal and connections of high capacity have higher blocking probability per unit line-speed than low capacity connections. The reason for this is that low line-speed connections groom better and fit easier into wavelengths than high line-speed connections. It is interesting to note that when the number of grooming nodes are around 10 to 15, the fairness ratio is close to 1. The MaxSum algorithm also has the highest fairness ratio when the grooming nodes are high, and the lowest fairness ratio (away from one) when there are no grooming nodes in the network. This motivates the need for effective schemes to achieve capacity fairness.

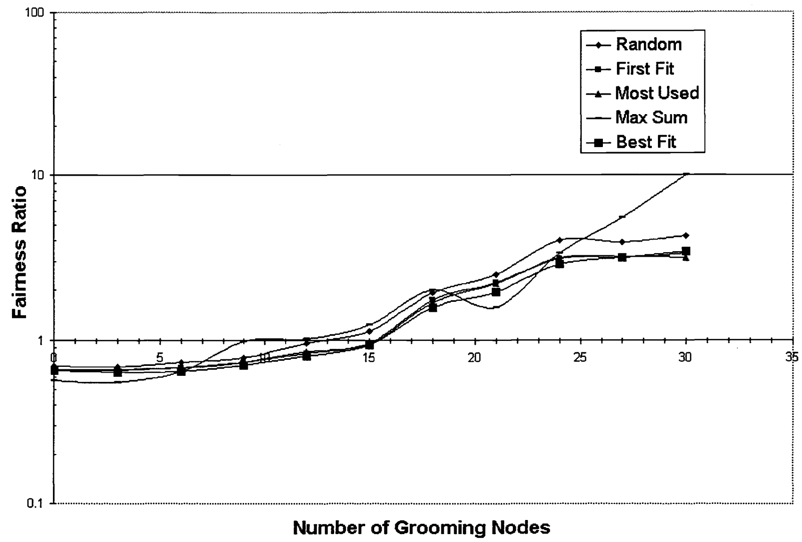

Figure 3. The fairness ratio versus number of WGXC nodes for a bidirectional 6×6 mesh-torus with $g = 4$ and $W = 5$.

Next we will study the performance of our connection admission control (CAC) scheme. We will compare the performance when the CAC algorithm is used along with the first-fit (FF) wavelength assignment scheme, and when the FF scheme is used without the CAC scheme. We assume the network scenario when there are no grooming nodes in the network. In the fairness ratio graph shown in Fig. 4, we find that both of the CAC schemes, *mean ratio* and *deviation ratio* achieve excellent fairness where the fairness ratio is equal to 1 when compared to First Fit which has a fairness ratio is less than one. This confirms that the CAC algorithm works very well under high loads to the network.

Now we would like to see the increase in overall network blocking probability per unit line-speed that is required to achieve the fairness. This graph is shown in Fig. 5. We find there is a relatively small and consistent increase in blocking performance of the CAC-FF scheme when compare to just the FF scheme. This shows that our scheme can achieve capacity fairness with little increase in overall network blocking probability per unit line-speed.

6. CONCLUSION

We have addressed the concept of capacity fairness in WDM networks with grooming capabilities. Such a network can consist of OADMs, optical crossconnect and traffic grooming equipment capable of switching traffic streams from one wavelength to another. In such networks, a call can request a low-rate traffic connection to be established between the source and destination. In this scenario of supporting low-rate circuit-switched traffic streams, the call request that asks for a high-capacity for its connection will encounter a higher probability of blocking than those which ask for a smaller fraction. We provided a qualitative and quantitative definition of capacity fairness. Current dynamic routing and wavelength assignment techniques were designed for conventional wavelength routing networks where the wavelength was the basic unit of bandwidth. These algorithms are not good at achieving capacity fairness. Therefore additional mechanisms such as connection admission control are required to achieve fairness in capacity. A good connection admission control scheme should provide capacity fairness while at the same time ensure that the increase in overall network blocking probability per unit line-speed is minimal. We proposed such a connection admission control scheme that ensures capacity fairness while at the same time ensures a small increase in blocking performance. We have studied the performance of the algorithm under limited conditions such as the mesh-torus

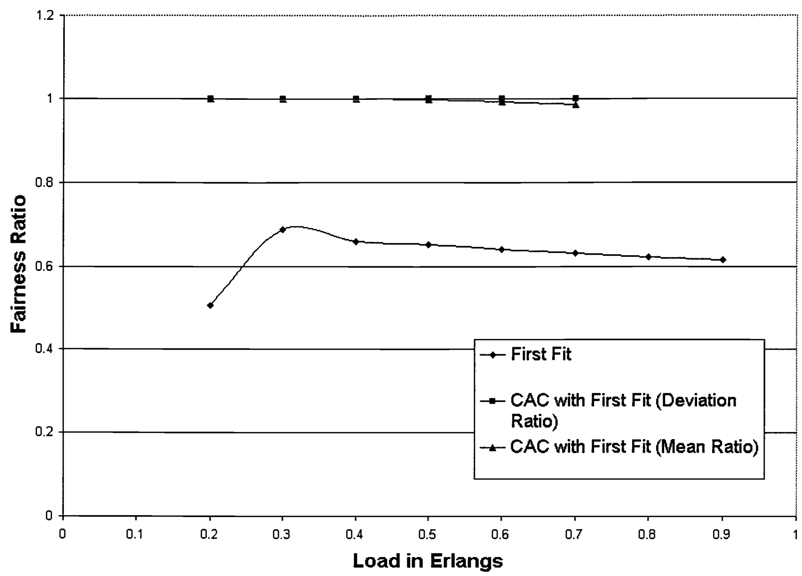

Figure 4. The fairness ratio versus node load in Erlangs for a bidirectional 6×6 mesh-torus with $g = 4$ and $W = 5$.

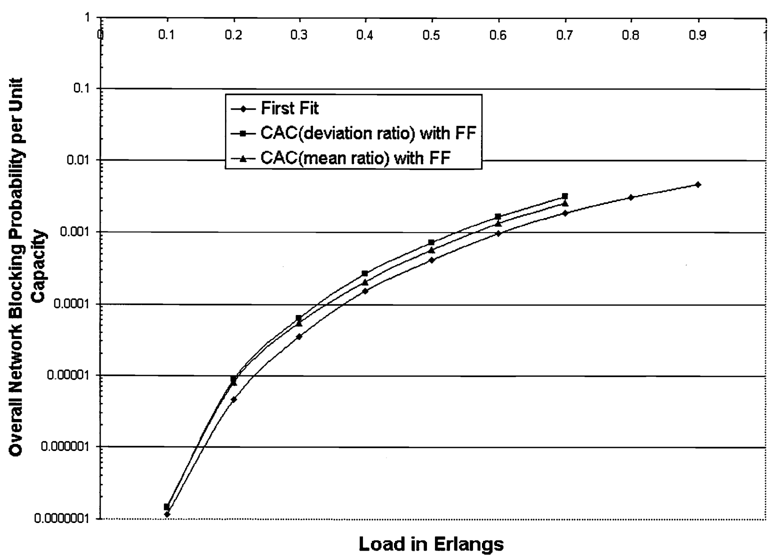

Figure 5. The overall network blocking probability per unit capacity versus node load in Erlangs for a bidirectional 6×6 mesh-torus with $g = 4$ and $W = 5$.

topology. Although this paper identifies the connection admission control method as a viable scheme to ensure capacity fairness, we need to study its performance under high and low loads, on other network topologies such as ring and arbitrary mesh networks, and using dynamic-routing methods.

ACKNOWLEDGEMENTS

This work was supported by the NSF under grant ANI-9973102.

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